AN INSTRUMENTATION SYSTEM FOR LETHALITY EVALUATION OF MISSILE INTERCEPT FLIGHT TESTS

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Abstract

This paper offers arguments to support the contention that a differential GPS measurement system is required for missile intercept flight testing. Simply stated, there is no other system capable of sufficiently accurate relative 3-dimensional position measurements at the point of impact or fusing to support lethality evaluations of precise weapon systems. Earlier work has proven that two-centimeter accuracy can be achieved with differential GPS in a missile intercept test environment. This paper will review the earlier work, discuss the nature of the lethality evaluation process, define the basic measurement system structure, discuss some important system tradeoffs, and identify hardware characteristics needed to implement a missile intercept evaluation system.

Introduction

Since the late 1980s The Johns Hopkins University's Applied Physics Laboratory (JHU/APL) has been actively involved in the design and development of instrumentation for missile intercept evaluations. We were responsible for the design of the Brilliant Pebbles (BP) instrumentation system, and although the program was canceled before that system achieved flight test status, the instrumentation was fully developed and flight qualified. We developed the first missile qualified GPS digital translator for that system.[1,2] GPS translators and the associated ground recording equipment provide for post-flight receiver operations. That is, the GPS signal data are recorded such that post-flight phase-locked-loop tracking can be accomplished during playback at a special tracking facility at JHU/APL. These capabilities were originally developed to support the Navy's Trident program, in a system known as *SATRACK*.[3]

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In 1990 and 1991, we participated in the Ballistic Missile Defense Organization's (BMDO) Exoatmospheric Reentry Intercept Subsystem (ERIS) flight test program. The interceptor and target for this program used Ballistic Missile Translators (BMTs) developed for the Range Applications Joint Program Office (RAJPO). We provided the post-flight tracking and analysis to support two ERIS tests. Our post-processing system was able to measure the relative geometry between the interceptor and target to an accuracy of 60cm.[4] We are continuing to support BMDO intercept testing in the current Integrated Flight Test series.

In 1993, we were asked if the ERIS technique could be used to provide relative trajectory measurements with greater accuracy. In a brief study, we concluded that the accuracy limitation of the ERIS system was due to the single frequency (L_1) narrow bandwidth (C/A-code) signal restrictions. The study identified an antenna, translator, and ground recorder configuration that we believed would achieve a two-centimeter accuracy. This is not a fundamental limit, it was set by our estimate of the antenna phase errors, and practical tracking bandwidths for this application. However, none of the required equipment then existed to test our conclusions.

Fortunately, in 1994, there was a need within the Extended Navy Test Bed (ENTB) system for a dual frequency (L_1 & L_2) wide bandwidth (P/Y-code) translator and the associated signal recording equipment. We developed the required ENTB equipment and it performed successfully in its first flight test in December 1995.[5] With the Navy's approval, we were able to use some equipment from our ENTB development program to conduct an IR&D project that demonstrated the conclusions of our 1993 study.

The demonstration project was accomplished at the High Speed Test Track at Holloman AFB. The results of the test are reviewed next. For anyone already aware of these test results or not interested in reviewing the test details, this discussion can be bypassed. The important point is that the Holloman test coupled with the earlier ERIS and BP experience have fully established the feasibility of a GPS translator-based two-centimeter vector measurement capability for missile intercept evaluations.

Holloman Test

A special test used to successfully validate the GPS two-centimeter measurement concept was conducted at the Holloman AFB High Speed Test Track on August 8, 1996. The test included two GPS translator equipped bodies, one rocket propelled on one rail and the other stationary on the second rail. Both bodies used the same type GPS antenna specifically designed for this test. The dynamic body used two S-band blade antennas, one to relay the translated GPS signals to the Track Data Center (TDC) and the second for other telemetry signals. S-band signals from the stationary body were carried by cable to a track-side blockhouse. Translated GPS signals were recorded at both sites using ENTB receiver/recording equipment. A more complete report of the demonstration project will be found in two earlier papers.[6,7]

The need to provide a high speed intercept-like test condition in a limited yet well controlled trajectory space, led to selection of the Holloman high speed test track. Figure 1 shows the basic geometry and defines the coordinate system for our measurements. Relative position vector measurements are defined in terms of three orthogonal components *(along-track, cross-track, vertical)*. The origin is at the center of the stationary body's GPS antenna. The surveyed relative position vector at closest approach is (0, 2.133, 0) meters. The high dynamic conditions as derived from an on-board accelerometer are shown in Figure 2. The dynamic body reached Mach 4 at Time-of-Closest-Approach (TCA).

The track is equipped with a location measurement system based on magnetic interrupters. Time-of-day is recorded as the sled passes each interrupter. The accuracy of this system, known as *Spots*, is limited by uncertainties in the exact position and timing of the interrupt. Higher precision, in the region of closest approach, was provided by additional instrumentation. Image Motion Compensation (IMC) cameras provided a single point measurement at TCA. The IMC camera picture gave a measurement of the position of the dynamic GPS antenna in relation to the track surface and center-line. In addition, a precision fiber optic system was used to accurately measure TCA and the time at three positions on either side of that point.

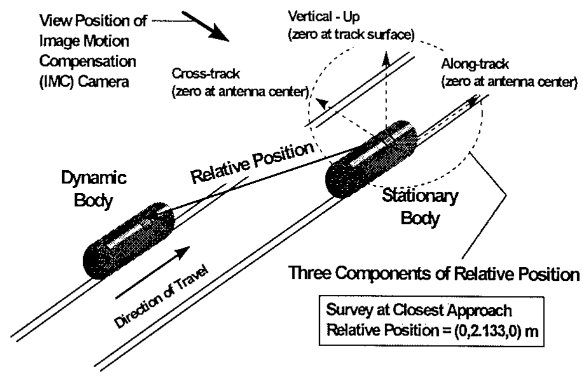

Figure 1. Relative position vector geometry.

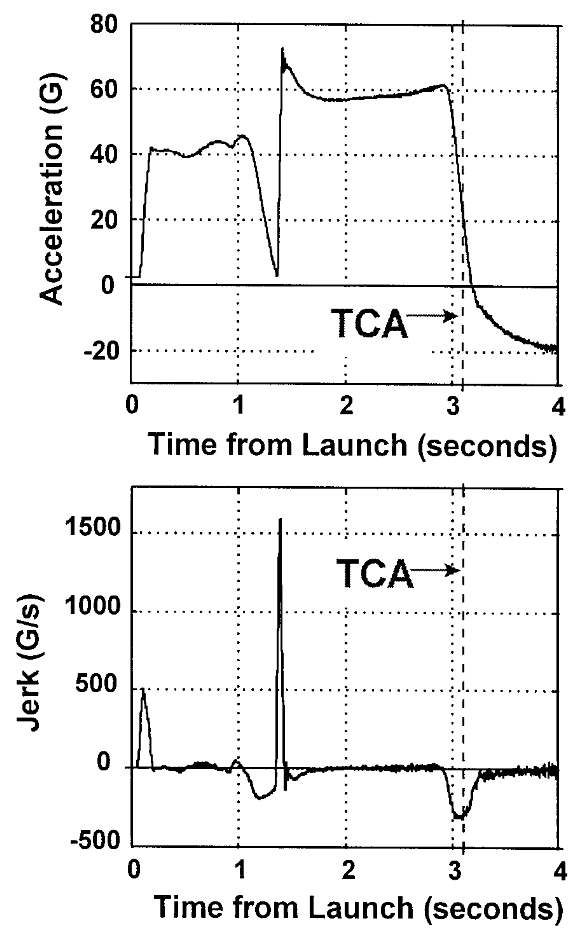

Figure 2. Sled acceleration and jerk profiles in high dynamic region near TCA.

The position of each fiber break cable are accurate to a small fraction of an inch. The absolute time of any break is accurate to less than 2 microseconds and the relative time between breaks is accurate to less than 200 nanoseconds. The independent instrumentation systems used for ground truth were developed and operated by Test Track staff.

Relative position vector differences between the GPS measurements and the optical survey are summarized in Table 1. The survey measurements combined with fiber optic and camera processing uncertainties are assessed to produce less than one centimeter error in the reference position used for comparison with the GPS data. The uncertainties tabulated are those associated with the GPS measurement process. The tabulated differences can only be considered relative position errors if the surveyed data is assumed to be errorless. In any event, the differences between the reference and GPS measurements are seen to be less than two centimeters in all coordinates, with the maximum difference in the vertical measurement. The data clearly verify that a translator-based GPS relative measurement system can provide two centimeter accuracy in a high dynamic environment.

Table 1
Relative Position Difference (GPS-Survey)

Component	Difference (cm)	Uncertainty (cm)
Along-track	1.1	0.8
Cross-track	-.03	0.6
Vertical	1.4	1.8

All the other intercept measurement issues relative to antenna design, velocity determination, and attitude were adequately addressed in the ERIS tests. The only outstanding issue was whether GPS signal tracking would allow carrier cycle range measurements in very high dynamic situations. This demonstration provided that assurance.

Lethality Evaluation

The following discussion presents the current methodology for lethality evaluation to support the instrumentation concepts we believe are needed.[8] Lethality evaluation presents a significant challenge in the domain of well controlled ground testing, but extending it into live flight tests is virtually impossible without a significant improvement in flight test instrumentation.

We recognize that precision missile interceptor system performance evaluation includes many complex and interrelated processes in addition to the lethality aspect. We also recognize that there are differences between performance evaluations of hit-to-kill and fragmentation weapons. Our goal in this discussion is to address the primary instrumentation issues in relation to the hit-to-kill weapon, in the belief that the same principles apply to all other weapons where their effectiveness depends on impacting or fusing with a precisely defined relative (interceptor-to-target) geometry.

It is acknowledged that the weapon systems and their targets present such a complex set of test variations that we can not expect to gather enough statistical test data to adequately predict their deployed performance. Weapon system performance estimates will be based on simulated engagements based on mathematical models. Even in the restricted domain of lethality evaluations, concerned only with the outcomes of impacts between a single interceptor and target, simulation and modeling is the only practical means for performance prediction.

Full-scale impact tests of interceptor-target pairs are currently conducted at the Holloman test track. In these tests, an interceptor flies off the test track into a suspended target. The test environment is good at controlling the impact geometry and very good at measuring the impact geometry. Furthermore, these tests allow for collection of the debris which provides for direct observation of impact effectiveness. Even if this test were perfectly representative, it would still be a daunting task to conduct such tests over any appreciable range of impact points, angles, and velocities. Instead, mathematical models are exercised with the sled test conditions to examine the degree to which the simulated results match the sled test results. The models will have been designed to *correlate* with previous test experience, but unless the models are perfect, model results will not exactly match the test results. Even if the model were perfect, a single test can not be expected to be statistically significant. The real hope is that the model is sufficiently accurate to at least provide an adequate statistical representation of the outcome of the impact. In any event the analyst will have done all that he can reasonably do with his current mathematical description of the process using the available sled test data. It must be somewhat of an art form to decide when the number of sled tests are sufficient to adequately characterize the impact model.

However, having accepted the impact model, simulations can now be run over a range of impact points, angles, and velocities to develop a statistical description of this *one* target's vulnerability to this *one* interceptor, over some limited range of impact parameters. The next effort is to decide how many other tests are needed to characterize target vulnerability over a sufficient range of impact parameters? Finally when an acceptable number of tests and simulations are completed, this target's vulnerability is sufficiently defined.

Unfortunately, we must finally admit that sled tests can't support the full range of expected impact parameters. One of the primary current shortfalls is that the impact velocities of the sled tests are considerably lower than those expected for some deployed weapon systems. To offset this shortfall, light gas gun testing is used. This testing is capable of providing representative impact velocities, but it is not capable of supporting full scale interceptors. Like the sled test, this testing provides good control and measurement of the impact geometry, and it allows direct debris collection. However, we now need to judge whether the scale model interceptor and target are good representations of the real items. Again the test and analysis community will have done the best job they can within the limited constraints of this test environment, and again data from these tests will provide an opportunity to assess the quality of the available impact models.

Assuming that the lethality community will have done all that it can to adequately define target vulnerability, the system flight test program need *only* develop the statistics associated with the probabilities that lethal impact geometry is achieved for any specific intercept attempt; a significant undertaking in itself. Based on our current judgment of lethal impact geometry, an instrumentation system with accuracy on the order of that demonstrated by the Holloman test will be needed to support model assessments for this aspect of the weapon system.

Some might suggest that the lethality of a system flight test engagement can be determined without precise knowledge of the relative interceptor-to-target geometry at impact. Such things as radar or optical signatures of the debris cloud resulting from the impact might be offered as positive indicators of a lethal impact. If we assume that such an indicator is absolute, it can score the success, but it can't describe the geometry that produced success. Was the impact lethal even though the hit-point was outside our current definition of the lethal zone? Was the lethal zone hit, but the impact not lethal? Questions like these can not be answered by this technique. However, if we couple precise geometry measurement support with an independent lethality indicator, each flight test adds data to the lethality model evaluation effort. Furthermore, before accepting that such things as debris cloud measurements provide absolute lethality detection, we should question how the models used for this assessment were derived. If we include precision geometry as a part of the system test, that data might also be used to provide increased confidence in the sensor's debris cloud model.

Debris cloud measurements may provide important data for lethality evaluation, and they should be used to their fullest capability. The important point is that application of these techniques is strengthened when combined with GPS measurements. Our major concern is that the development of statistically representative models for precision missile intercept systems will be data starved. The range and variation of system engagements will require our very best efforts at each point in the development and operational test environment. Differential GPS measurements provide the *string* needed to tie the various observations together. From the lethality test perspective it is useful to think of differential GPS as providing impact geometry information equal to that provided in sled tests. Admittedly we do not have the same level of control over the impact, but each impact represents *real* weapon system performance and will provide another valid sample to test the impact models. In this sense, every differential GPS instrumented flight test provides lethality test data similar to a sled test.

Differential GPS is the only means that can measure the impact geometry with an accuracy roughly equivalent to what is obtained from a well instrumented sled test. While radars can provide reasonably accurate line-of-sight measurements of range, their angular resolution is essentially useless at this level of accuracy. A minimum of three typical instrumentation radars are needed to provide even crude positioning information, and it is always difficult to achieve good measurement geometry, due to site limitations. Even three wide bandwidth (~500MHz) imaging radars with good geometry will not provide positioning data anywhere close to the accuracy provided by the GPS measurement. Optical instruments can provide high resolution measurements, but their geometry is also limited by site constraints. However the most serious difficulty with optical instruments are their visibility limitations.

Target-mounted sensors are the other class of instruments normally considered for this application. Doppler radar techniques are used in many applications, but not at the level of accuracy being considered here. Impact position detection techniques based on measuring cable breaks in a fiber optic web mounted on the target can provide the right level of accuracy. However, this measurement will only measure the point impacted on the target. It does not measure what point on the interceptor hit that point on the target. Neither does it provide any significant information with regard to impact angle or velocity (although these data might be obtained from other instrumentation). When target impact position data is combined with other sensor data to attempt a more complete description of the impact geometry, the results will still be limited relative to differential GPS. Only the target hit point can be observed at the centimeter level; the other instruments will not define the interceptor impact point with that accuracy. The impact point measurement technique is unique with regard to observing details of target breakup, and it or some variant might be useful for detecting multiple impact points. Whatever its unique capability, it does not replace the function provided by the GPS measurement. This type of instrumentation would certainly be useful for flight qualifying the deployed GPS instrumentation. Seeker telemetry is required to evaluate its in-flight performance, and it can be tempting to think this data can be used to measure intercept geometry. However, the seeker can not truly be used to evaluate itself. Seeker telemetry data are very important to the evaluation, but again it is the accurate independent geometry provided by GPS that accomplishes seeker evaluation.

We conclude this discussion by suggesting that given the significant expense of intercept system flight tests and the need to associate impact conditions and geometry with lethality, it is imperative that proper instrumentation be provided. Relative GPS measurements are the only means for providing sufficiently accurate 3-dimensional relative position measurements to support lethality evaluations in the flight test environment, and translator-based GPS techniques are the only proven instrumentation. Furthermore, this instrumentation can support other important aspects of flight testing. We know from previous experience that this technique can support model validation in guidance and control, and in ERIS we have used this system to provide an independent evaluation of seeker performance. We also know that it can support range safety. Are there some shortcomings? Certainly, but no other system offers the accuracy and range of support capabilities of differential GPS. Furthermore, this is the only system that is truly available at all test sites.

Basic GPS Measurement Considerations

The basic elements of the measurement system are shown in Figure 3. Both the interceptor and target have subsystems consisting of a dual frequency GPS antenna and translator, and a downlink antenna. Each tracking station data recovery subsystem (target and interceptor) will receive and record the translated GPS signals. The recorded signal data are sent to the post-flight processing subsystem where the relative trajectory measurements are derived. Trajectories for each vehicle are obtained from multiple measurements of satellite-to-satellite differences. This technique has the benefit of removing all common mode errors beyond the GPS antennas. Absolute trajectory uncertainties of less than 2 meters in position and less than 1 cm/sec in velocity are readily achieved.

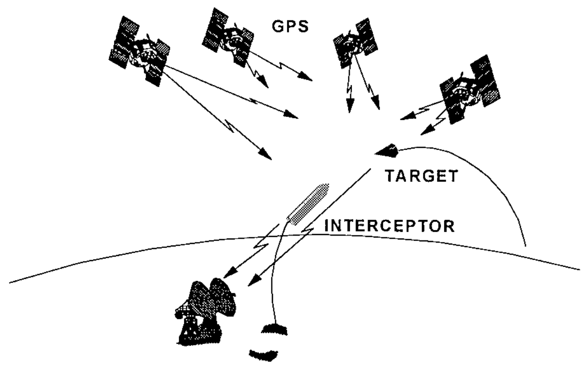

Figure 3. GPS Measurement System.

A particular satellite-to-satellite range difference (determined from tracking GPS range code modulations) unambiguously defines a hyperbolic surface with the two GPS satellite positions as foci and containing the tracked vehicle's antenna location. Three such surfaces (four satellite measurements) locate the vehicle position. Higher precision trajectory measurements are achieved by using integrated signal phase data (determined from phase-locked loop tracking of the GPS carrier signals) to connect between independent range derived positions. In all practical instances, absolute trajectory uncertainty is dominated by the systematic errors that are highly correlated in the two trajectory measurements. In the relative position vector measurement, signal tracking noise is the dominant error. The differential solution based on direct processing of carrier smoothed range data will not achieve the highest possible accuracy.

The highest measurement accuracy is based on using carrier phase measurements to determine range precision to a small fraction of the signal wavelength. While carrier phase noise is small, phase measurements are not normally useful for ranging because they are ambiguous at the signal wavelength level (i.e., the range is known to within a fraction of 19 cm, but how many cycles there are in any slant range measurement is unknown). In the precision differential measurement, the basic data are second differences (i.e., the difference between identical satellite-to-satellite differences as measured at the two vehicles). Each double difference phase measurement will produce multiple surfaces of revolution, each separated by one wavelength. Carrier phase noise will cause each surface to be slightly fuzzy.

The true relative position vector must end where all surfaces intersect at a common point. Finding this point would be easy if the differential position uncertainty from carrier phase smoothing of range (i.e., the result of the unambiguous solution) were small enough or the surface fuzziness due to carrier phase noise were zero! In the real case, a search technique is used to examine all possible combinations of integers in an allowable search volume surrounding the computed/estimated relative position vector derived from the carrier smoothed range solution. The ambiguity combination yielding the smallest fitting residuals is the chosen solution, and the uncertainty is equal to a small fraction of the carrier wavelength. This process requires a minimum of one additional in-view satellite (i.e., a minimum of five satellites, or satellites and ground transmitters). We attempted to process the ERIS flight data this way without success. With the single frequency narrow bandwidth data, no single ambiguity set stood out as an obvious solution.

The ambiguity search is greatly aided by using both GPS signals (L_1 and L_2). *Wide laning* and *narrow laning* techniques use tracking data from the two GPS frequencies to create computational wavelengths from the difference and sum frequencies (i.e., 86cm and 11cm). When this technique is combined with the range noise performance available from P/Y-code tracking, ambiguity resolution is very strong. Furthermore, the two frequencies provide redundant independent solutions, which increase the likelihood of success. Although the dual frequency capability may not be required to overcome ionospheric errors in this measurement, a robust solution in a high dynamic environment is virtually impossible without the dual frequency P/Y-code measurement approach.

Accurate impact analysis also depends on a comprehensive description of the velocity and attitudes of the two bodies at the time of impact. Measurement of the relative velocity of the two bodies is a straightforward extension of the GPS technique used for measuring relative position (i.e., velocity is observed in the differential GPS Doppler data). Attitude measurements require additional information. In many instances, the target and interceptor have independent means for sensing attitude. As long as the attitude sensor data is telemetered, the attitude histories of both bodies can be reconstructed from that data. In those cases where the attitude accuracy is limited by the available sensor, GPS can be used to greatly refine attitude measurement precision by analytically combining the two measurements. If needed, a multiple GPS antenna configuration can extract attitude directly from GPS signals.

<u>Translator versus Receiver</u>

The first question usually asked is why not use GPS receivers instead of translators? The primary reason for using translators is that they reduce risk. If one or more phase-locked loops in either receiver drop lock at a critical time, the lost data can never be recovered. Unexpected phase jumps due to antenna motion or vehicle dynamics may easily produce these problems just when the interceptor is making its final trajectory adjustments. Considering the high cost of conducting an interceptor flight test, this one potential shortcoming would be sufficient for some of us to reject the receiver approach.

However, there are even additional drawbacks. Receivers: 1) are more complex , 2) require presets for initial acquisition and signal security, and 3) may be limited by time-to-first-fix when antenna visibility time is short. Also individual tracking loops within each receiver, and most surely between the two receivers, may have different and varying characteristics during the flight. In contrast to this, a translator: 1) is a simple radio relay requiring no signal tracking or message recovery functions, 2) needs no presets or GPS security considerations, and 3) the post-flight tracking can recover data in any short span where signals exist (within tens of milliseconds of their availability). Furthermore, since the post-flight tracking is accomplished in a laboratory environment using the same receiver for both translators, the potential for varying characteristics between tracking loops is minimized. Finally it should be noted that even if the receiver works perfectly, the translator solution will still be superior. Since post-flight tracking can be iterated at will, tracking loop performance can be optimized for any particular

circumstance. Tracking aids can be refined and loop bandwidths adjusted to optimally match the test flight conditions; no practical real-time receiver can provide this capability. Considering the accuracy requirements and the importance of flight test success, we conclude, that translators are the only sensible choice.

Downlink Frequency

Let us consider selection of a translator downlink frequency. In all our prior applications we selected S-band to take advantage of the telemetry infrastructure that was already in-place for missile flight test support. By adding one additional input to a frequency multiplexer in each vehicle the translator could use the existing vehicle downlink antenna. Translator signal recovery and recording at the ground station is accomplished by simply cabling to an existing S-band multiplexer patch panel. The receiver/recorder function is accomplished by heterodyning the preamplifier signals to near baseband where in-phase and quadrature samples are recorded. In our ENTB system, the equipment that accomplishes this function is packaged in an instrument suitcase that weighs only 42 pounds and can easily sit on top of a small table. Use of an S-band downlink continues to be a good logic, but some have raised concerns that current demands for telemetry space are already becoming restrictive without this additional requirement.

In those cases where additional S-band space is not available, another downlink frequency can be quite practical. Because the vehicles must necessarily use omni-directional antennas and the ground station uses a tracking antenna, the translator output power is independent of frequency (i.e., the translator output power required at C-band is the same as that required at S-band). Therefore the only penalty for changing downlink frequency is that it adds an antenna to each vehicle and it adds another feed and preamplifier to the telemetry tracking antenna. The additional vehicle downlink antennas may be accomplished with two small patches, as will be described later.

Downlink Bandwidth

The primary benefit attributed to using a receiver instead of a translator is that it greatly reduces the downlink bandwidth requirement. This should be no surprise, it is the inverse of all the reasons a translator is desired. Because the receiver completes the tracking process within each vehicle, the downlink information is compressed. However, as indicated above, we believe this advantage is actually a disadvantage. That aside, how shall we set the translator downlink bandwidth?

We first need to deal with the dual frequency requirement. Recognizing that GPS has two frequencies to allow for correction of ionospheric refraction errors, and that in a close differential measurement the ionospheric errors are very highly correlated, might lead you to conclude that this application could operate with a single GPS frequency. However, as previously noted, the need to derive range from phase measurements requires cycle ambiguity resolution. Our analysis and test results[7] have clearly shown that ambiguity resolution without dual frequency tracking is not practical in a highly dynamic environment.

Now, turning our attention to downlink bandwidth, there are two things to consider: 1) GPS signal overlap, and 2) minimum channel bandwidth. Beginning with the desire to minimize downlink bandwidth, we ask the question, is it better to overlay the two GPS signals in a common bandwidth or to split the total bandwidth into two adjacent signal channels? With regard to range tracking precision, the overlay is the correct choice. This is easily seen by considering the case of a 20MHz output bandwidth (i.e., the GPS transmission bandwidth). Here we can either split the band into two 10MHz signals or overlay both signals in the full output bandwidth. One choice limits the translated GPS signal transmission bandwidth by 2:1 and the other decreases the signal-to-noise (SNR) by 2:1. However range tracking precision is inversely proportional to the signal transmission bandwidth and inversely proportional to the square root of SNR. Therefore the gain in bandwidth has more value than the loss in SNR.

This same conclusion applies for any bandwidth less than 20MHz, but in these cases we are accepting both a bandwidth and a SNR reduction. At bandwidths above 20MHz the additional bandwidth would be used to reduce overlap (i.e., the signals would be moved apart to fill the available output bandwidth). At 40MHz the signals are fully separated and there is no gain beyond this point.

Having concluded that for output bandwidths up to 20MHz the two GPS signals should be totally overlaid, we now see that the choice for a dual frequency design will not impact the downlink bandwidth, as long as we can accept the 3dB SNR loss. We should consider the relative impact of other bandwidth choices. If we increased the bandwidth to 40MHz, range tracking precision would only increase by the square root of two (i.e., this would give two adjacent 20MHz channels and thereby increase the SNR for each by 3dB). It did not seem reasonable to

double our bandwidth for this relatively small gain. On the other hand, if we reduced our total bandwidth to 10Mz, this would decrease range tracking precision by two (i.e., double range tracking noise). Given the steeper penalty for changes in this direction we decided to hold the 20MHz bandwidth for the ENTB design. Having now successfully completed the Holloman test with this design, we would be hesitant to draw back very far from the 20MHz bandwidth.

There is another disadvantage to overlaying the two GPS signals (apart from the noise increase). With the two signals totally overlaid, an interference signal in either translator input channel is imposed on both signals in the post-flight tracking process. However, given the strong emphasis throughout the navigation community to keep the GPS signal bands free of interference, this is not a serious concern. We have certainly seen nothing in our experience which suggests this should be a problem.

Before leaving this discussion, it should be pointed out that bandwidth issues for translators should be referenced to other tracking systems, not telemetry systems. For example a moderate resolution imaging radar will use a bandwidth on the order of 500MHz, and it is not unreasonable for them to use 1GHz. You can fit 25 to 50 translators in the space of one of these radars. A recent presentation[9] indicated that three imaging radars could measure the interceptor-to-target relative position vector to an accuracy of 20cm. Compared to that, a system based on two translators using a total bandwidth of 40MHz and providing 2cm accuracy is very efficient, with regard to spectrum utilization.

<u>Antenna Considerations</u>

Recovering position information with centimeter resolution requires a detailed understanding of the GPS antenna motions on the two vehicles. Antenna phase effects can introduce electrical changes that superimpose an apparent motion term on top of the antenna's physical motion. The GPS antennas on both vehicles need coverage in all directions to obtain signals through their full range of motion. The apparent tracked position (i.e., phase center) of an antenna will generally vary as the signal direction changes. An acceptable antenna must either have phase center variations that are small relative to one centimeter or its phase variations must be known and correctable to that level. One useful antenna design is referred to as a *ring* antenna. This antenna provides good signal coverage except for two small solid angles in the nose and tail direction. The nominal phase center for this type of antenna is at the center of the ring. A well designed small ring antenna approaches ideal performance over a large region. However, corrections may still be required when signals move close to the nose or tail direction. This antenna design was successfully applied for the ERIS tests.

The recommended approach is based on multiple independent simple antennas. A set of three or four single patch antennas can be time multiplexed through a single translator such that each can be independently tracked. The multiplex frequency is set high enough to allow each phase-locked loop to maintain continuous tracking as long as the signal does not move out of the coverage area for that patch. The maximum physical linear dimension of each antenna is only a few inches and they are only a fraction of an inch deep. The apparent phase center for such antennas is very stable over a hemispherical region. Tracking data from all in-view satellites over a wide range of missile motions with the defined mechanical positions of the patch antennas provides a solid basis for separating antenna electrical phase center motions from their physical motions. A beneficial byproduct of this design is the ability to measure vehicle attitude.

S-band antenna design is somewhat less critical. The primary interest in this design is to provide continuous coverage at the tracking site (i.e., avoid data drop outs). A ring antenna is usually a good choice. If a ring can't be used, we had success in the BP system using polarization diversity based on two small S-band patches. In any event, small light weight designs are easily realized, not only at S-band, but at any reasonable downlink frequency.

<u>Analog versus Digital Translators</u>

There are many detailed differences between digital and analog translators, but from a system design perspective only a few are important. The primary reason for developing the GPS/Telemetry Transmitter (GTT) for BP was that the program required encryption of the translated GPS signals. Given that requirement, a digital translator had to be developed. Other benefits were derived from the additional flexibility provided by this design. Most importantly, for the GTT, we were able to produce a composite design that accomplished the functions of telemetry encryption and data transmission with GPS signal translation and encryption. The single package that accomplished all these functions was smaller and lighter than the telemetry transmitter and encryptor that it replaced. In effect, the GPS translator function was added to the interceptor with a weight and volume benefit. Since the interceptor was quite small, this was a significant aspect of the GTT design.

Digital designs also allow for flexible communications options. For example, multiphase modulation techniques can be used to reduce transmission bandwidth with an appropriate increase in the required transmit power. The ability to combine all telemetry and translator bit streams into a common communications channel allows for full optimization of the communications system within the available power/bandwidth constraints. These techniques may be important to the communications design, but the information requirements for the translator data are not fundamentally different. The digital translator must still provide the same information content that is derived from the minimum acceptable bandwidth required of the analog translator.

Summary of GPS System Considerations

It is our strong belief that differential GPS instrumentation is needed to properly support missile intercept flight tests. Within the domain of implementation choices for such a system we believe that two choices are absolutely required and prudence demands a third choice. Specifically, dual frequency wide bandwidth GPS signal tracking and special GPS antenna design considerations are absolutely required. These two choices are needed regardless of all other GPS implementation options. The key system design decision is translator or receiver. It is not impossible to use a receiver and this choice provides for dual frequency wide bandwidth tracking and has virtually no downlink bandwidth requirement. However, the risks associated with the receiver choice are, in our opinion, unacceptable.

Having selected the translator approach, the issues of downlink frequency and bandwidth become the primary design consideration. We already know that a 20MHz bandwidth will meet the requirement and 2MHz will not. We do not know if a bandwidth between 2 and 20MHz will be adequate, but we seriously doubt that anything less than 10MHz will suffice. We have already conducted a Trident flight test that included two 20MHz translators and four telemetry transmitters without difficulty. Therefore, we know that it is possible to support two translators with S-band downlinks in a missile flight test. However, if specific program requirements preclude the use of an S-band downlink, the system can use a different band. We would recommend that a different downlink frequency choice be made rather than reduce the translated signal bandwidth. If a different downlink band is selected, and wider bandwidth is available, the signal overlay constraint might be removed to improve performance.

The choice between analog and digital translators is secondary, in regard to performance capability. If GPS signal downlink encryption is required, the translator must be digital. Otherwise either choice can support the same accuracy. This and all remaining design choices should be based on minimizing the instrumentation impact on the interceptor. Having developed the BP instrumentation, we are sensitive to the limitations of small interceptors. Second priority, with regard to minimum impact, is given to the target instrumentation. The ground station recording and post-processing configurations are readily adapted to those choices that are most sensible for the interceptor and target configurations.

Hardware Implementation

Specific hardware choices can not be identified without requirement inputs for a particular program. However, we can offer some important insights. The interceptor will require a GPS antenna, a translator, and a downlink antenna. The second generation ENTB translator should meet all requirements, if an analog translator can be used. This design is qualified for Trident missile and reentry body flight applications. It has up to a four-way antenna multiplex capability, dual frequency GPS P/Y-code overlay, a 20MHz downlink bandwidth, and a 5 watt S-band output power. The package dimensions are 4 x 5.5 x 1.2 inches, it weighs one pound, and it requires 25 watts of DC power.

The GPS antenna requirement can be met with three or four simple dual frequency patches. By themselves these are small and light weight, their final size and weight will be controlled by mounting and aerodynamic considerations. Two downlink antenna patches have similar characteristics and their final size and weight will also be controlled by mounting and aerodynamic considerations. The downlink antenna network will also require one power combiner to connect the two patches. If an existing downlink antenna is used, it will save the weight and space of these components. Ignoring a shared downlink antenna option, the interceptor would have to support five or six antenna patches, one power combiner, one translator, and six or seven RF cables. The total weight exclusive of mounting provisions is on the order of two pounds.

Another translator option might be provided from the Translated GPS Range System (TGRS) program. This is a RAJPO program that has specified

a translator design with a volume of 8.5 to 10 cubic inches and a weight between 0.75 and one pound. If this design or a slight variant can meet the requirements, then the translator size and weight might be slightly reduced, but the antennas and their mounting and cabling requirements would not be changed. Therefore the weight of this configuration, exclusive of mounting provisions, might be on the order of 1.75 pounds.

The integration effort for the interceptor can be significant. We recognize that mass distribution and balance are important to the interceptor design. The translator, which is the largest single component, has mounting flexibility. If the GPS antenna cables need to be long, preamplifier assemblies can be incorporated with each antenna patch. The weight difference for patches with or without preamplifiers is not significant, but it is still preferable to avoid the extra components if possible. We should attempt to minimize the RF cable lengths on the output side of the translator. However, if this is not possible, the power amplifier could be separated from the translator to allow more freedom in configuring component hardware.

The most difficult integration issue will likely be antennas. Providing surface mounted antennas on high speed bodies is a non-trivial task. An antenna configuration that meets all mechanical and aerodynamic requirements will be a dominant design factor. On the positive side, the system signal requirements using the multiplex antenna concept, allow for considerable flexibility with regard to location. The primary requirement is to assure that the arrangement provides for signal reception in all directions. There are no requirements for symmetry and there is no need to match antenna cable lengths. The processing requirements are satisfied by simply knowing the locations of each antenna and the lengths of their corresponding cables. The downlink antenna patches need only satisfy the interceptor mechanical and aerodynamic requirements, and provide for satisfactory viewing from the tracking station(s). The phase characteristics of this antenna have only secondary importance to the processing system.

The target can use the same hardware components used by the interceptor. Similar integration issues will apply, except that the target will probably allow more freedom with regard to internal mounting provisions and total weight. It should be noted that the mechanical requirements, for both interceptor and target, are not significantly different for a receiver design system concept. The only differences are related to the choice of a downlink antenna. If the translator system can use the same downlink antenna as the telemetry system, the external designs for either system concept would be identical. The interior designs would be different, but there is no fundamental basis for one being simpler than the other.

Ground station and processing system equipment, facilities, and software present no fundamental issues with regard to satisfying the requirement to successfully instrument a two-centimeter differential GPS capability for missile intercept testing. They can be addressed after the flight hardware configurations are selected. The ENTB recording system already provides the additional ground station capability needed for the ENTB analog wide bandwidth translator, and it provided that capability for the Holloman test. Similarly the Trident post-flight processing facility has successfully processed the recorded data for the ENTB and Holloman tests. Therefore, in those applications where a wide bandwidth translator with an S-band downlink is acceptable, all major components and subsystems are already available.

Conclusion

Support for lethality evaluation of interceptor flight tests will require more precise interceptor-to-target relative geometry measurements than have ever been achieved. A relative GPS measurement technique capable of the required measurement accuracy has been demonstrated. With the exception of implementation details associated with integrating proven devices with a specific interceptor and target, this instrumentation is ready to be applied. In particular, the key issue is integration of GPS antennas with the interceptor and target. Otherwise, all components of a proven instrumentation system are available now. Given the high value of interceptor flight test data, every effort should be made to assure that robust precision instrumentation is available as early as possible.

Even for those systems eventually requiring a digital translator, the proven ENTB subsystems could be used to quickly validate that acceptable interceptor and target antenna configurations can be realized. Subsequent hardware variations to alter downlink frequency or to change to a digital translator would not invalidate the results of such a test. The measurement technique is not sensitive to downlink frequency, and whether the signals are sampled in the interceptor and then sent to the ground (digital translator) or transmitted to the ground and then sampled (analog

translator) is irrelevant to the post flight tracking system. Therefore the results of such a test would apply to any instrumentation variant that provides the same GPS antenna characteristics and the same signal bandwidths. Given the potential importance of early interceptor flight test results, use of quickly available resources may be highly beneficial.

A system test using ENTB components would provide full GPS signal capability. The data collected from a flight test using these components could be used to analyze reduced bandwidth options. With digital pre-filtering, the flight test data can be reprocessed to define system accuracy versus bandwidth. This will define a minimum translator bandwidth for any specific interceptor test requirement.

To restate our primary conclusion, a relative GPS instrumentation system suitable to precision missile intercept evaluation testing is ready to be applied to specific test programs. There are no unanswered questions with regard to applying the technique, only design of specific interceptor and target configuration details remains to be completed. Furthermore, there are resources available to allow early flight testing to both validate designs of critical interceptor and target components and to provide early flight test results.

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